ARMY RESEARCH LABORATORY

An Experimental Microwave Heating System for a 120-mm Munition

by Robert Tan, Tim Vong, and Stephen Howard

ARL-TR-1317 September 1997

Approved for public release; distribution unlimited.

Army Research Laboratory
Adelphi, MD 20783-1197

ARL-TR-1317 **September 1997**

An Experimental Microwave Heating System for a 120-mm Munition

Robert Tan, Tim Vong, and Stephen Howard
Sensors and Electron Devices Directorate

Abstract

This report details an experimental microwave heating system designed for use with a 120-mm munition. The system operates at 2.45 GHz, using slotted waveguide radiators. The reported temperature measurements show relatively uniform heating of a surrogate 120-mm munition. Experiments at the Army Research Laboratory have shown that a munition's propellant heated for a few minutes by microwaves to 49°C has characteristics similar to those of propellant that has been temperature-conditioned to 49°C for several hours. In particular, this heating increases the munition's muzzle velocity about 5 percent, thus enhancing its performance.

Contents

Figures

Table

Introduction

This report describes the design and testing of a microwave system for heating a 120-mm munition. It is well known that the performance of direct-fire kinetic-energy ammunition improves with increased preignition temperature. At 49°C, muzzle velocity increases approximately 5 percent above that of a munition at an ambient temperature of 25°C. Previous experiments at the Army Research Laboratory (ARL), based on earlier insitu microwave propellant heating concepts and techniques originated by Scannell [1], have shown that propellant heated to 49°C by microwaves over a few minutes has ignition characteristics similar to those of propellant that has been temperature-conditioned for several hours to 49°C [2]. These initial experiments used a crude microwave system that did not uniformly distribute the microwave energy and, therefore, did not uniformly heat the propellant [3]. Thus, a microwave system was developed that could do this. Uniform heating is essential if very rapid heating is desired; otherwise, the heating is limited by the thermal conduction time.

This new system is designed to (1) accept a typical 120-mm munition and (2) heat the munition more uniformly to 49°C within 10 s, given enough microwave power. The time required to raise the propellant temperature a given amount is essentially a linear function of the microwave power given by

$$\Delta t(s) = \frac{m(\mathrm{kg})c_p(\mathrm{J/kgK})\Delta T(\mathrm{K})}{P(\mathrm{W})}\ , \tag{1}$$

where P is the power, m is the mass, c_p is the specific heat, ΔT is the rise in temperature and Δt is the time to raise the temperature. For the 120-mm munition, we estimated that it contains 7.9 kg of propellent that has a specific heat of 1340 J/kgK. Therefore, it takes 26 kW to raise the propellent 25°C in 10 s assuming all the microwave power is absorbed by the propellant. However, measurements of the shell casing have shown that 74 percent of the microwave power is transmitted to the propellant, 23 percent is reflected, and the remaining 4 percent is absorbed by the casing. Thus, about 33 kW would be needed to raise the temperature by 25°C in 10 s. This power can currently be generated with off-the-shelf commercial magnetrons. These calculations assume that the temperature of all the propellent is increased 25°. Computer simulations and laboratory measurements suggest that only the propellant in the outer portion of the munition needs to be heated to obtain the same ballistic improvement as obtained by heating the entire propellant load. If this proves to be true, less power will be required.

Design

The 120-mm munition has a diameter of 15.5 cm. The length of the area with propellent to be heated is about 46 cm, as shown in figure 1. The heating system is designed to uniformly heat the propellent through the casing of the 120-mm munition. The casing is made of a nitrate-impregnated cardboard coated with a thin antistatic layer containing aluminum.

The heating system consists of six identical waveguide sections that have four radiating slots. Each section is fed at the base as shown in figures 2 and 3. The result is a total of 24 radiating slots, which are used to distribute the microwave energy over the surface of the munition. The six slots in the feed are numbered 1 through 6, starting with slot number 1 at the input of the feed. For convenience, the slots in the six sections are numbered from 1 to 24, with slots 1 through 4 on section 1 (fed by the base slot 1), with slot 1 being the slot one-quarter wavelength ($\lambda/4$) from the shorted end, and slots 5 through 8 on section 2, and so on. The system is constructed using standard WR-284 waveguide and is designed to operate at 2.45 GHz. This frequency was chosen because the propellent is quite lossy at 2.45 GHz and because inexpensive magnetrons, such as those used in commercial microwave ovens, produce this frequency and are readily available.

Figure 1. Cross section of 120-mm munition.

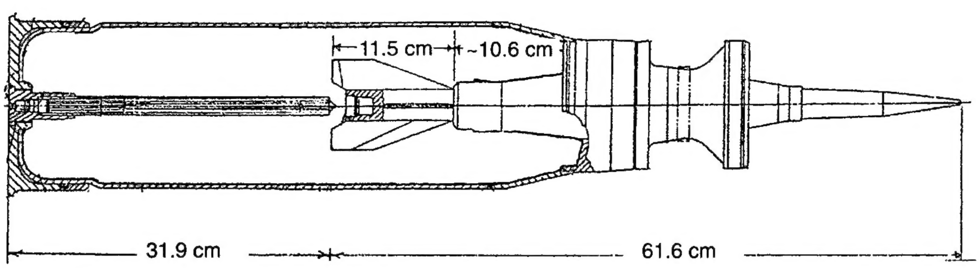


Figure 2. Waveguide section (with radiator slots and tuning screws) alongside base feed.

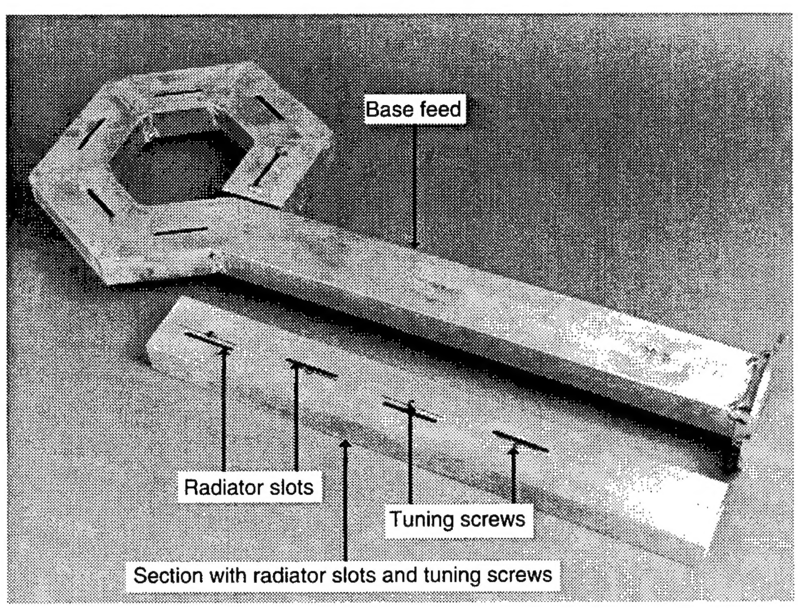
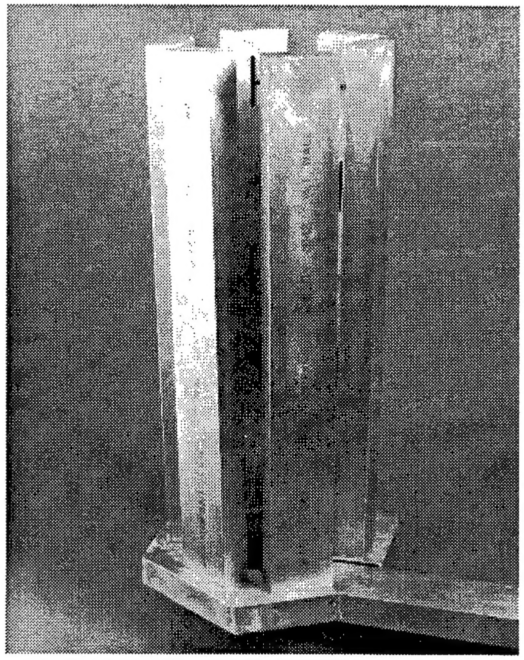


Figure 3. 2.45-GHz microwave heating system.



Slot Placement

Figure 4 shows the dimensions of the six identical waveguide sections, each of which is fed by a slot in the base. Each waveguide section has four slots arranged on either side of the centerline on its broad interior wall. All the slots are a half free space wavelength ($\lambda/2$ = 15.16 cm) long and are placed one-half the waveguide wavelength ($\lambda_g/2$ = 29.41 cm) apart. Waveguide wavelength is given by

$$\lambda_g = \lambda\left[\varepsilon_r - (\lambda/\lambda_c)^2\right]^{-0.5} , \tag{2}$$

where the waveguide cutoff wavelength, λ_c, is twice the broad dimension (a), or $\lambda_c = 2a$, and ε_r is the relative permittivity of the material filling the guide. In this case, the guide is filled with air (ε_r = 1) and a = 7.21 cm. The last slot is placed $\lambda_g/4$ from the end of the guide, which is short circuited. The slots in the feed are also $\lambda/2$ long and separated as close to $\lambda_g/2$ as possible, given the mechanical restraints of forming a circular structure to place the radiating elements relatively equally around the 120-mm munition. The dimensions are shown in the mechanical drawings in the appendix. The current distribution in a short-circuited guide is shown in figure 5. The current pattern repeats itself every $\lambda_g/2$, with only the current direction changing every $\lambda_g/2$. For a slot to radiate, it must cut the path of the current, which is why the slots are offset from the center. The larger the offset from the center, the more power is radiated because more current is flowing across the slot at the edges of the guide. The slots are placed on alternate sides of the centerline so that the current flows in the same direction across each slot. This provides a same-phase field radiating from each slot, preventing nulls in the field due to phase cancellations, which would not uniformly heat the munition. To determine the exact location of each

Figure 4. Position and dimensions of six slotted waveguide sections.

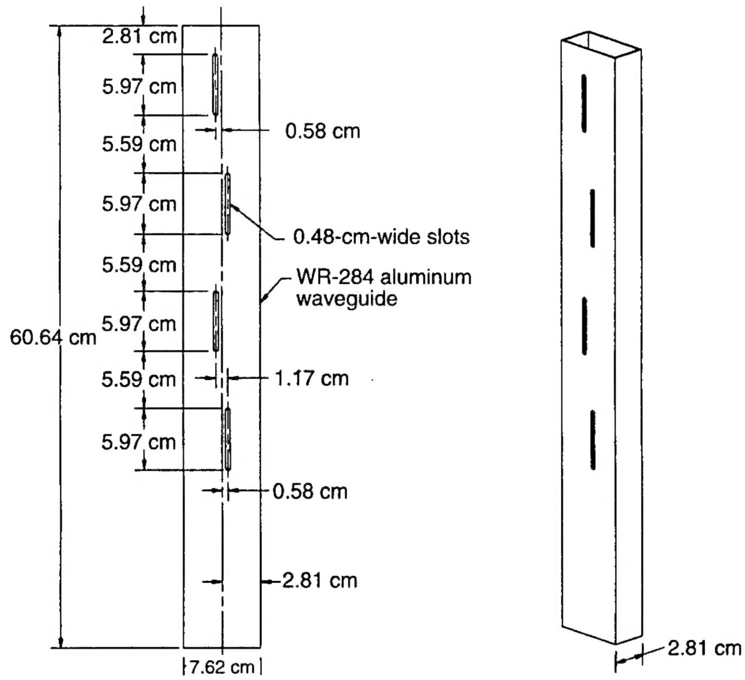
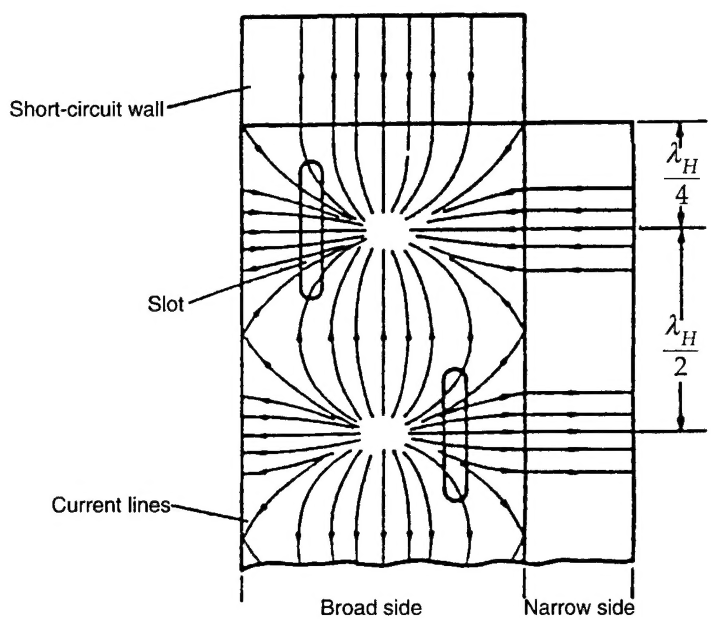


Figure 5. Current distribution in shorted waveguide section.



slot from the centerline, each slot is represented as a shunt impedance. If the slot is $\lambda_g/2$ long, the reactance becomes zero and each slot can be modeled by real shunt resistance (R). The normalized conductivity Z_L/R is given by

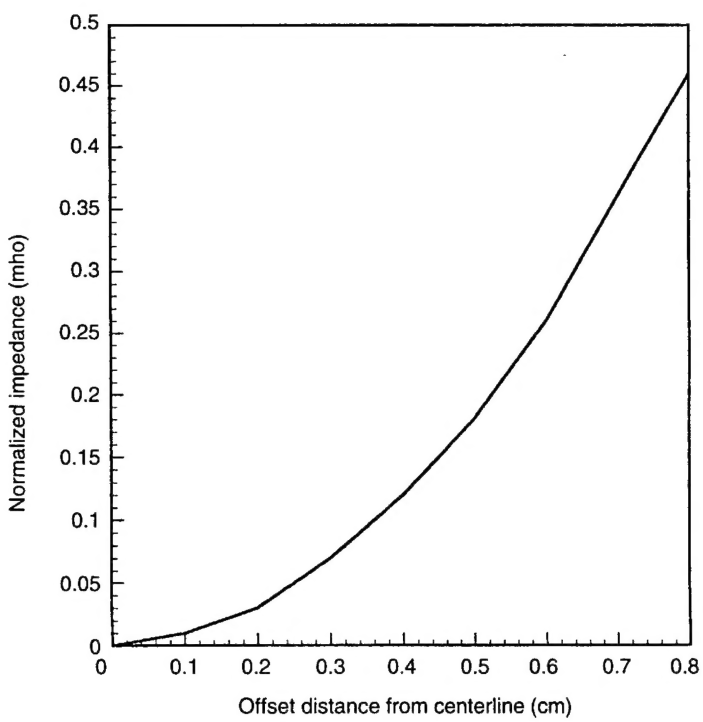
$$\frac{Z_L}{R} = \frac{480}{73\pi}\frac{a}{b}\frac{\lambda_g}{\lambda}\cos^2\left(\frac{\pi\lambda}{2\lambda_g}\right)\sin^2\left(\frac{\pi x_1}{a}\right), \tag{3}$$

where Z_L is the characteristic impedance of the guide, λ_g is the waveguide wavelength, λ is the free-space wavelength, $a \times b$ is the interior cross-section dimensions of the waveguide, and x_1 is the offset distance from the centerline of the slot [4]. To match the multiple slots with minimum reflection, the resulting shunt resistance of the slots must equal the characteristic impedance of the guide or, for four slots,

$$Z_L = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4}} . \tag{4}$$

If all slots are positioned the same, all values of R are equal and $Z_L/R = 1/N$ where N is the number of slots. Therefore, in our case with four slots per waveguide section, $Z_L/R = 1/4$. In figure 6, x_1 is plotted as a function of Z_L/R, given $\lambda = 12.24$ cm, $\lambda_g = 23.1$ cm, $a = 7.2$ cm, and $b = 3.4$ cm. From figure 6, $x_1 = 0.59$ cm for $Z_L/R = 1/4$. The feed section has 6 slots, so $Z_L/R = 1/6$ and, again from figure 6, $x_1 = 0.5$ cm.

Figure 6. Offset distance from centerline (x_1) as function of normalized impedance.



Slot Tuning

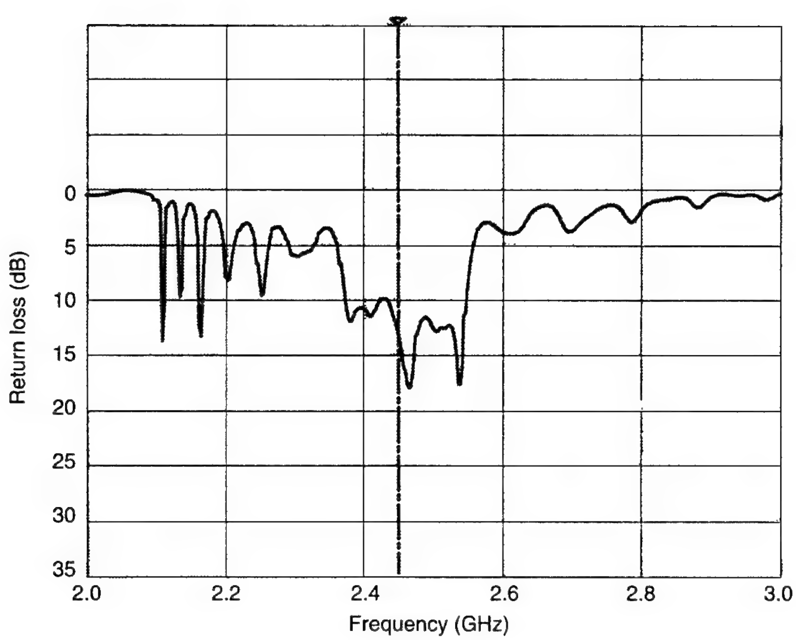
Moving the position of a section slot is not the only way to adjust the power radiated; it can also be adjusted by placing a tuning screw next to the slot, as shown in figure 3. Changing the length of the screw effectively moves the position of the slot [4].

Fabrication and Measurements

Initially a single test section was fabricated with four slots. The measured return loss is plotted in figure 7 and shows a return loss of 14 dB at 2.45 GHz. With these favorable results, the complete heating system could be fabricated with no modifications to the calculated dimensions. The heating system was fabricated from standard aluminum WR-284 waveguide. (See the appendix for mechanical drawings.) Unfortunately, every other slot in each of the six sections was fabricated with $x_1 = 0.47$ cm instead of 0.59 cm waveguide; to compensate, tuning screws were added toward the center of the guide adjacent to each slot, as shown in figure 3. The return loss measurement of the heating system is 15 dB at 2.45 GHz, as shown in figure 8. The transmission from each slot was measured by placing a waveguide-to-coaxial transition over each slot and measuring the transmission loss using a network analyzer. Ideally, the transmission measurement should be –13.8 dB if each slot radiated 1/24 of the input power. The actual measurements of the system with no tuning are shown in table 1.

The standard deviation is 0.98 dB with a maximum difference of 3 dB between the slot radiating the most power and the slot radiating the least power. With tuning screws, the power transmitted from each radiator slot was adjusted for more even distribution of power. Table 1 also shows the transmission measurement after tuning the system.

Figure 7. Measured return loss for test section with four slots.



After tuning, the standard deviation is reduced to 0.83 dB, with a maximum difference of 3 dB of transmitted power between the slot radiating the most power and the slot radiating the least power.

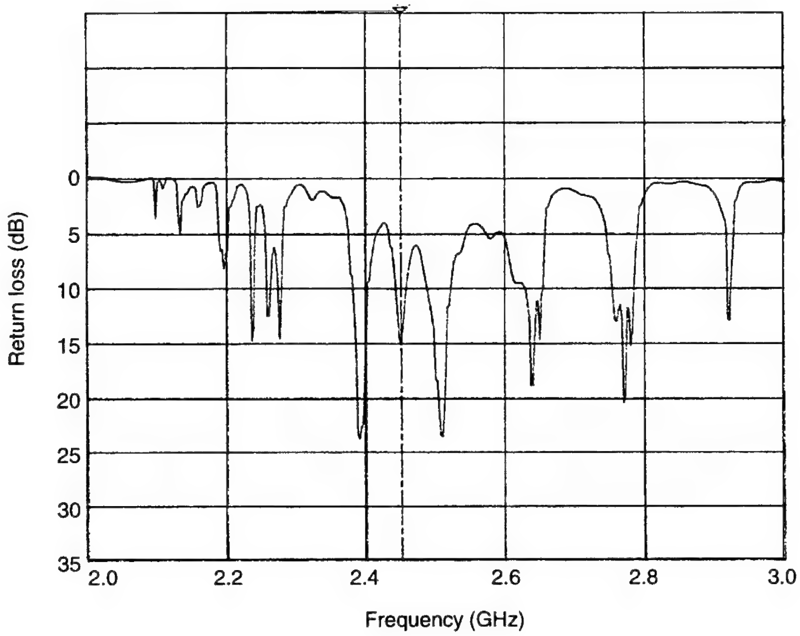


Figure 8. Measured return loss for complete system.

Table 1. Microwave transmission (by slot) before and after tuning, and temperature after 2 min heating.

Slot no.	S_{21} (dB)		Temperature after 2 min heating (°C)
	Before tuning	After tuning	
1	–15	–14	33
2	–15	–15	37
3	–16	–15	38
4	–15	–15	38
5	–14	–14	38
6	–16	–14	37
7	–14	–13	39
8	–16	–14	37
9	–16	–16	35
10	–17	–16	36
11	–15	–15	36
12	–15	–15	36
13	–16	–13	32
14	–15	–14	33
15	–14	–14	34
16	–15	–14	35
17	–16	–14	32
18	–17	–15	33
19	–17	–15	34
20	–16	–15	34
21	–16	–15	32
22	–17	–14	33
23	–14	–13	35
24	–15	–15	36

Heating Measurements

For safety reasons, a live 120-mm munition could not be used in these initial heating experiments. Instead a 15-cm-diameter, 46-cm-long acrylic tube was filled with a surrogate that had a permittivity similar to the actual propellent [3]. The relative permittivity of graphitized and nongraphitized JA2 propellent is $3.5 - j0.65$ and $4.1 - j0.75$, respectively.

The surrogate used for the experiments is a mixture of sand, 1 percent table salt, and 3.75 percent water by weight, which had a measured permittivity of $3.8 - j0.76$. To quickly assess the uniformity of the heating, we used the sand mixture in conjunction with thermal paper to generate a picture of the temperature variations in the sand. The thermal paper was formed into a cylinder and placed around the inner diameter of the acrylic tube and also was cut into 15-cm-diameter circles, which were layered axially in the sand. The thermal paper begins to show darkening at 70°C; therefore, the sand needed to be heated to at least this temperature. Because of the available source power, about 10 min elapsed before the thermal paper showed any darkening. The images made with the thermal paper were qualitative and were used in making adjustments to the radiator tuning screws. Unfortunately, the images did not photocopy well enough for publication in this report. A thermistor was also used to take temperature measurements in the sand. Twenty-four positions were measured 2.5 cm radially into the sand in front of the 24 section slots. Table 1 also shows the temperature in degrees Celsius after 2 min of heating. The standard deviation is 2°C.

Conclusions

A microwave heating system was designed and tested to heat the propellent in a 120-mm munition. A mixture of sand, salt, and water that has roughly the same permittivity as the propellant was used in the heating experiments. Both thermal paper and thermistors were used to measure the temperature throughout the propellent. The thermal paper was only used to give a qualitative picture of the uniformity of the heating and to assist in making adjustments to the system. The thermistor measurements were made in 24 positions spaced evenly throughout the propellant. After 2 min of heating, the standard deviation of the measured temperature was 2°C. This deviation can probably be improved by correcting the 20-percent error made in positioning half the section slots. The tuning screws helped to correct the error but could not completely compensate for the error in slot placement. Based on the mass of the propellant, its specific heat, and the efficiency of the microwave system, 26 kW of microwave power are needed to raise the temperature of the propellent in a 120-mm munition by 25°C in 10 s.

Work is being done that suggests that only a fraction of the propellent needs to be heated to obtain essentially the same ballistic improvement as heating all the propellent. If this is true, the microwave energy required is reduced in proportion to the mass of the propellant to be heated.

References

1. E. P. Scannell, "Microwave Ignition," AAI Corporation, Independent Research and Development (IRAD) Project No. AW-68553 (1988), I-134–166.

2. S. L. Howard, L. M. Chang, T. T. Vong, E. P. Scannell, and S. L. Kaplan, "Microwave Heating of Propellent: A Conceptual Approach to Ballistic Improvement of Tank Ammunition," *Proceedings of 1995 JANNAF Propulsion Meeting*, CPIA **I**, *630* (1995), 141.

3. S. L. Howard, L. M. Chang, T. T. Vong, E. P. Scannell, R. Tan, and C. R. Buffler, "Microwave Heating of Propellent: A Rapid Heating Approach to Ballistic Improvement of Ammunition," *Ballistics '96* **1** (1996), 273.

4. S. Silver, *Microwave Antenna Theory and Design*, New York: McGraw Hill (1949), 291–301.

Appendix—Mechanical Drawings for Microwave Heating System

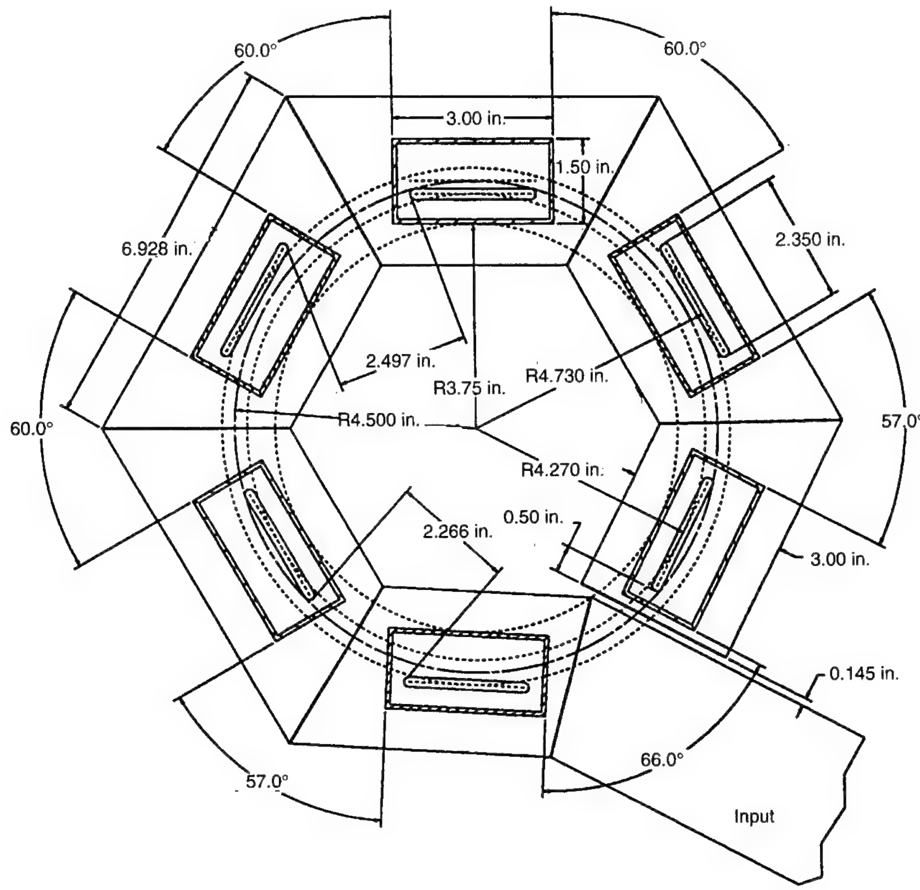


Figure A-1. Microwave input feed for leaky waveguide system.

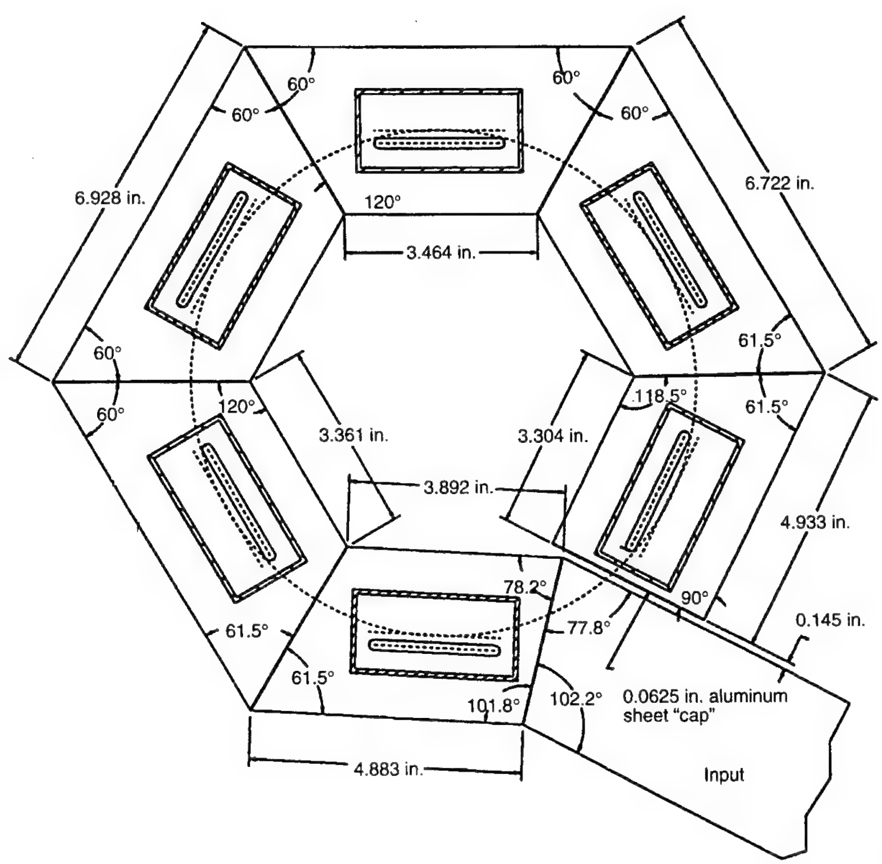


Figure A-2. Waveguide input feed for leaky waveguide system.

Figure A-3. Waveguide input feed for leaky waveguide system showing position of slotted waveguide radiators.

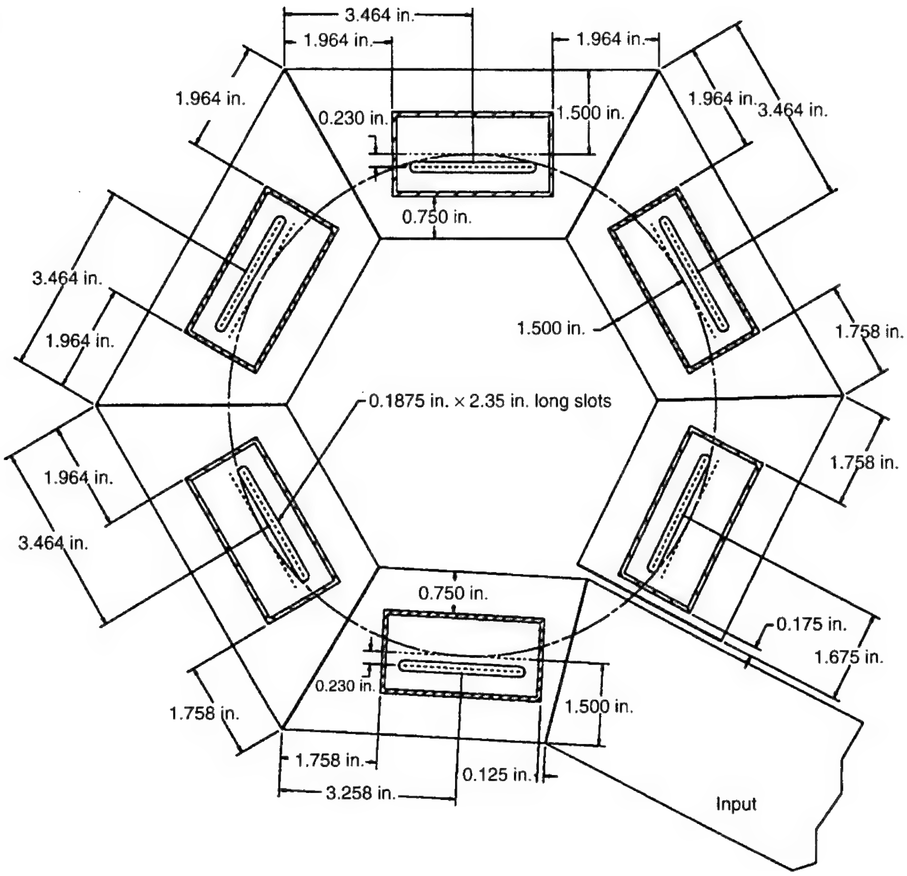
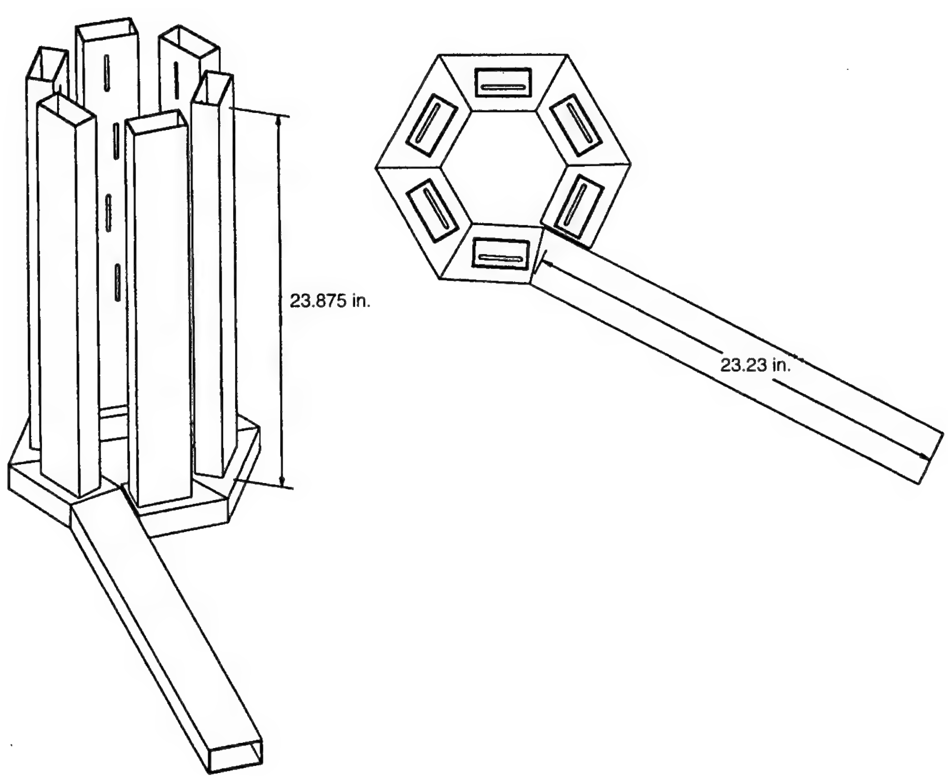


Figure A-4. Leaky waveguide assembly drawing.



Distribution

Admnstr
Defns Techl Info Ctr
Attn DTIC-OCP
8725 John J Kingman Rd Ste 0944
FT Belvoir VA 22060-6218

Central Intlgnce Agency
Attn J Backofen
NHB Rm 5N01
Washington DC 20301-7100

Central Intlgnce Agency
Ofc of the Cntrl Rfrnces Dissemination Br
Rm GE 47 HQS
Washington DC 20502

DoD Explosives Safety Bd Hoffman Bldg 1
Rm 856 C
2461 Eisenhower Ave
Alexandria VA 22333-0001

Hdqtrs Defns Special Weapons Agency
Attn A Fahey
Attn D Lewis
6801 Telegraph Rd
Alexandria VA 22310-3398

Ofc of the Secy of Defns
Attn ODDRE (R&AT) G Singley
Attn ODDRE (R&AT) S Gontarek
The Pentagon
Washington DC 20301-3080

PEO
Armored Syst Moderization
Attn SFAE-ASM-BV
Warren MI 48397-5000

Battle Lab Integration & Techl Dirctrt
US Army Train & Doctrine Cmd
Attn ATCD-B J A Klevecz
FT Monroe VA 23651-5850

CECOM
Attn PM GPS COL S Young
FT Monmouth NJ 07703

CECOM RDEC Elect Systems Div Dir
Attn J Niemela
FT Monmouth NJ 07703

CECOM
Sp & Terrestrial Commctn Div
Attn AMSEL-RD-ST-MC-M H Soicher
FT Monmouth NJ 07703-5203

DARPA
Attn B Kaspar
Attn J Pennella
Attn L Stotts
3701 N Fairfax Dr
Arlington VA 22203-1714

Dir Benet Labs
Attn AMSTA-AR-CCB-T S Sopok
Attn AMSTA-CCB-RA G A Pflegl
Attn AMSTA-CCB-RA G P O'Hara
Attn AMSTA-CCB-S F Heiser
Watervliet NY 12189-4050

DIR HQ Trac RPD
Attn ATCD-MA
FT Monroe VA 223651-5143

Dir of Assessment and Eval
Attn SARD-ZD H K Fallin Jr
103 Army Pentagon Rm 2E673
Washington DC 20310-0163

Dpty Assist Secy for Rsrch & Techl
Attn SARD-TR R Chait Rm 3E476
Attn SARD-TT D Chait
Attn SARD-TT K Kominos
Attn SARD-TT R Reisman
Attn SARD-TT T Killion
Attn SARD-TT F Milton
The Pentagon
Washington DC 20310-0103

DUSD Space
Attn 1E765 J G McNeff
3900 Defense Pentagon
Washington DC 20301-3900

Hdqtrs Dept of the Army
Attn DAMO-FDQ D Schmidt
400 Army Pentagon
Washington DC 20310-0460

Distribution

MICOM RDEC
Attn AMSMI-RD W C McCorkle
Redstone Arsenal AL 35898-5240

Ofc of the Product Mgr 166mm Howitzer
M109A6 Paladin
Attn SFAE-AR-HIP-IP R De Kleine
Picatinny Arsenal NJ 07806-5000

OSD
Attn OUSD(A&T)/ODDDR&E(R) J Lupo
The Pentagon
Washington DC 20301-7100

PM Abrams Tank Sys
Attn SFAE-ASM-B
Warren MI 48397-5000

PM AFAS
Attn SFAE-ASM-AF-E J Shields
Attn SFAE-ASM-AF-E LTC A Ellis
Attn SFAE-ASM-AF-E T Kuriata
Attn SFAE-ASM-AF-Q W Warren
Picatinny Arsenal NJ 07806-5000

PM PEO Armaments
Tank Main Armament Sys
Attn AMCPM TMA
Attn AMCPM TMA 105
Attn AMCPM TMA 120
Attn AMCPM TMA H Yuen
Picatinny Arsenal NJ 07806-5000

PM US TACOM
Attn AMCPM-ABSM T Dean
Warren MI 48092-2498

Radford Army Ammo Plant
Attn AMSTYA-AR-QA HI Lib
Radford VA 24242-0298

SDIO DA
Attn E Gerry
Pentagon
Washington DC 20505

CDR Army ARDEC
Attn SMCAR-AEE J Lannon
Attn SMCAR-CCH-T L Rosendorf
Attn SMCAR-CCH-V C Mandala

CDR Army ARDEC (cont'd)
Attn SMCAR-CCH-V E Fennell
Attn SMCAR-CCS
Picatinny Arsenal NJ 07806-5000

US Army ARDEC Prod Base Mdrnztn Agency
Attn SMSMC-PBM A Siklosi
Attn SMSMC-PBM E L Liabson
Picatinny Arsenal NJ 07806-5000

US Army ARDEC
Attn AMSTA-AR-FSA-F S Floroff
Attn SMCAR-AES S Kaplowitz
Attn SMCAR-FS T Gora
Attn SMCAR-FS-DH J Feneck
Attn SMCAR-FSA-T M Salsbury
Attn SMCAR-FSC G Ferdinand
Attn SMCAR-FSN N K Chung
Attn SMCAR-FSS-A B Machek
Attn SMCAR-FSS-A L Pinder
Attn SMCAR-FSS-A R Kopmann
Attn SMCAR-AEE-B B Brodman
Attn SMCAR-AEE-B D Downs
Attn SMCAR-AEE-B J O'Reilly
Attn SMCAR-AEE-B P Hui
Attn SMCAR-AEE-B P O'Reilly
Attn SMCAR-AEE-B R Cirincoine
Attn SMCAR-AEE-B Rutkowski
Attn SMCAR-AEE-B S Bernstein
Attn SMCAR-AEE-B S Einstein
Attn SMCAR-AEE-B S Westley
Attn SMCAR-AEE-WW C Hu
Attn SMCAR-AEE-WW D Wiegand
Attn SMCAR-AEE-WW J Pinto
Attn SMCAR-AEE-WW M Mezger
Attn SMCAR-AEE-WW P Lu
Picatinny Arsenal NJ 07806-5000

US Army ATC
Attn STECS-LI R Hendricksen
Aberdeen Proving Ground MD 21005

US Army Avn Rsrch, Dev, & Engrg Ctr
Attn T L House
4300 Goodfellow Blvd
St Louis MO 63120-1798

Distribution

US Army BMDS Cmd Advanced Techlgy Ctr
PO Box 1500
Huntsville AL 35807-3801

US Army CECOM Rsrch, Dev, & Engrg
Attn R F Giordano
FT Monmouth NJ 07703-5201

US Army Command & General Staff College
FT Leavenworth KS 66027

US Army Edgewood Rsrch, Dev, & Engrg Ctr
Attn SCBRD-TD J Vervier
Aberdeen Proving Ground MD 21010-5423

US Army Field Artillery CTR & School
Attn ATSF-CN
FT Sill OK 73503-5600

US Army Info Sys Engrg Cmd
Attn ASQB-OTD F Jenia
FT Huachuca AZ 85613-5300

US Army Materiel Sys Analysis Agency
Attn AMXSY-D J McCarthy
Aberdeen Proving Ground MD 21005-5071

US Army Matl Cmnd Dpty
CG for RDE Hdqtrs
Attn AMCRD BG Beauchamp
5001 Eisenhower Ave
Alexandria VA 22333-0001

US Army Matl Cmnd
Prin Dpty for Acquisition Hdqrts
Attn AMCDCG-A D Adams
5001 Eisenhower Ave
Alexandria VA 22333-0001

US Army Matl Cmnd
Prin Dpty for Techlgy Hdqrts
Attn AMCDCG-T M Fisette
5001 Eisenhower Ave
Alexandria VA 22333-0001

US Army Natick Rsrch, Dev, & Engrg Ctr
Acting Techl Dir
Attn SSCNC-T P Brandler
Natick MA 01760-5002

US Army NGIC
Attn AMXST-MC-3
220 Seventh Stret NE
Charlottesville VA 22901-5396

US Army Rsrch Dev & Stndrdztn Group UK
Attn R E Richenbach
PSC 802 Box 15
FPO AE 09499-1500

US Army Rsrch Ofc
Attn D Mann
Attn Techl Lib
PO Box 12211
Research Triangle Park NC 07709-2211

US Army Rsrch Ofc
Attn G Iafrate
4300 S Miami Blvd
Research Triangle Park NC 27709

US Army Simulation, Train, & Instrmntn Cmd
Attn J Stahl
12350 Research Parkway
Orlando FL 32826-3726

US Army Spcl Warfare Schl
Attn Rev & Trng Lit Div
FT Bragg NC 28307

US Army Tank-Automtv Cmd Rsrch, Dev, & Engrg Ctr
Attn AMSTA-TA J Chapin
Warren MI 48397-5000

US Army Tank-Automtv & Armaments Cmd
Attn AMSTA-AR-TD C Spinelli
Bldg 1
Picatinny Arsenal NJ 07806-5000

US Army Test & Eval Cmd
Attn R G Pollard III
Aberdeen Proving Ground MD 21005-5055

US Army Trac FT Lee
Attn ATRC-L Cameron
FT Lee VA 23801-6140

Distribution

US FAC&S
Attn ATSF -CO-MW E Dublisky
Attn ATSF-CN P Gross
FT Sill OK 75303-5600

USAASA
Attn MOAS-AI W Parron
9325 Gunston Rd Ste N319
FT Belvoir VA 22060-5582

USACECOM R&D Techl Lib
Attn AWQNC-ELC-IS L R Myer Ctr
FT Monmouth NJ 07703-5301

Nav Rsrch Lab
Attn Code 4410 E Oran
Attn Code 4410 J Boris
Attn Code 4410 K Kailasante
Attn Techl LIb
Washington DC 20375-5000

Nav Surfc Warfare Ctr
Attn C Gotzmer
Attn J Consaga
Attn K Rice
Attn S Mitchell
Attn S Peters
Attn T C Smith
Attn Techl Lib
Indian Head MD 20640-5000

Nav Surfc Warfare Ctr
Attn Code 730
Attn Code R 13 R Bernecker
Silver Spring MD 20903-5000

Nav Surfc Warfare Ctr
Attn Code G33 T Doran
Attn G30 Guns & Munitions Div
Attn G32 Guns Sys Div
Attn Code E23 Techl Lib
17320 Dahlgren Rd
Dahlgren VA 22448-5000

Nav Surfc Warfare Ctr
Attn Code 388 C F Price
Attn Code 388 T Boggs
Attn Code 3895 R Derr
Attn Code 3895 T Parr
China Lake CA 93555-6001

Ofc of Naval Techlgy
Attn Ont 213 D Seigel
800 N Quincy Stret
Arlington VA 22217-5000

AFOSR NA
Attn J Tishkoff
Bolling AFB DC 20332-6448

AL LSCF
Attn J Levine
Attn L Quinn
Attn T Edwards
Edwards AFB CA 93523-5000

WL MNME
Attn Energetic Materials Br
2306 Perimeter Rd STE 9
Eglin AFB FL 32542-5910

GPS Joint Prog Ofc Dir
Attn COL J Clay
2435 Vela Way Ste 1613
Los Angeles AFB CA 90245-5500

Ofc of the Dir Rsrch and Engrg
Attn R Menz
Pentagon Rm 3E1089
Washington DC 20301-3080

OLAC-L TSTL
Attn D Shiplett
Edwards ARF CA 93523-5000

Special Assist to the Wing Cmndr
Attn 50SW/CCX CAPT P H Bernstein
300 O'Malley Ave Ste 20
Falcon AFB CO 80912-3020

USAF SMC/CED
Attn DMA/JPO M Ison
2435 Vela Way Ste 1613
Los Angeles AFB CA 90245-5500

WL MNAA
Attn B Simpson
Eglin AFB FL 32542-4434

WL MNSH
Attn R Drabsczuk
Eglin AFB FL 32542-5434

Distribution

Lawrence Livermore Natl Lab
Attn L 355 A Buckingham
Attn L 355 M Finger
PO Box 808
Livermore CA 94550-0622

Sandia Natl Labs
Attn R Carling
Combstn Rsrch Facility
Livermore CA 94551-0469

Sandia Natl Labs
Attn 8741 G A Benneditti
PO Box 969
Livermore CA 94551-0969

Nasa Langley Rsrch Ctr
Attn MS 408 D Witcofski
Attn MS 408 W Scallion
Hampton VA 32605

ARL Electromag Group
Attn Campus Mail Code F0250 A Tucker
University of Texas
Austin TX 78712

California Institu of Techlgy Jet
Propulsion Lab
Attn MS 125 224 L Strand
4800 Oak Grove Dr
Pasadena CA 91109

CPIA JHU
Attn H J Hoffman
Attn T Christian
10630 Little Patuxent Pkwy Ste 202
Columbia MD 21044-3200

Georgia Inst of Techlgy Schl of
Aerospace Engrng
Attn B T Zinn
Attn E Price
Attn W C Strahle
Atlanda GA 30332

Southwest Rsrch Inst
Attn J P Riegel
6220 Culebra Rd
San Antonio TX 78228-0510

University of Austin Texas Inst for
Advanced Techlgy
Attn T M Kiehne
4030 2 W Braker Lane
Austin TX 78759-5329

University of Illinois Dept of Mech Eng
Attn H Krier
144MEB 1206 W Green Stret
Urbana IL 61801

University of Minnesota Dept of Mech Eng
Attn E Fletcher
Minneapolis MN 55455

AAI Corp
Attn D Cleveland
Attn J Frankle
PO Box 126
Hunt Valley MD 21030-0126

Aerospace Hercules Inc
Attn R Cartwright
100 Howard Blvd
Kenville NJ 07847

AFELM the Rand Corp
Attn Lib D
1700 Main Stret
Santa Monica CA 90401-3297

Allegheny Ballistics Lab Hercules Inc
Attn T F Farabaugh
Attn W B Walkup
PO Box 210
Rocket Center WV 26726

Alliant Techsystems Inc
Attn Techl Lib
PO Box 1
Radford VA 24141-0299

Alliant Techsystems Inc
Attn J Bode
Attn J Kennedy
Attn M Swenson
Attn MN11-1428 C Candland
Attn MN11-2626 L Osgood
Attn R Becker

Distribution

Alliant Techsystems Inc (cont'd)
Attn R Buretta
Attn R E Tompkins
600 Second Stret NE
Hopkins MN 55343

Arrow Techlgy Assoc Inc
Attn W Hathaway
PO Box 4218
South Burlington VT 05401-0042

Batelle
Attn TWSTIAC
Attn V Levin
505 King Ave
Columbus OH 43201-2693

Batelle PNL
Attn C Bampton
PO Box 999
Richland WA 99352

Dir for MANPRINT
Ofc of the Deputy Chief of Staff for Prsnnl
Attn J Hiller
The Pentagon Rm 2C733
Washington DC 20310-0300

ELI Freedman & Assoc
Attn E Freedman
2411 Diana Rd
Baltimore MD 21209-1525

General Applied Sci Lab
Attn J Erdos
77 Raynor Ave
Ronkonkama NY 11779-6649

General Electric Com Tactical System Dept
Attn J Mandzy
100 Plastics Ave
Pittsfield MA 01201-3698

Hercules Inc
Attn B M Riggleman
Hercules Plaza
Wilmington DE 19894

IITRI
Attn M J Klein
10 W 35th Stret
Chicago IL 60616-3799

Martin Marietta Defns Sys
Attn G Keeler
100 Plastics Ave Rm 2260
Pittsfield MA 01201

MBR Rsrch Inc
Attn M B Reuven
601 Ewing Stret Ste C 22
Princeton NJ 08540

Olin Corp
Attn F E Wolf
Badger Army Ammo Plant
Baraboo WI 53913

Olin Ordnance
Attn A F Gonzalez
Attn D W Worthington
Attn E J Kirschke
PO Box 222
ST Marks FL 32355-0222

Olin Ordnance
Attn H A McElroy
10101 9th Stret N
ST Petersburg FL 33716

Physics International Lib
Attn H W Wampler
PO Box 5010
San Leandro CA 94577-0599

Princeton Combstn Rsrch Labs Inc
Princeton Corporate Plaza
Attn N A Messina
Attn N Mer
11 Deerpark Dr Bldg IV Ste 119
Monmouth Junction NJ 08852

Rockwell Intrntl Rocketdyne Div
Attn BA08 J Flanagan
Attn BA08 J Gray

Distribution

Rockwell Intrntl Rocketdyne Div (cont'd)
Attn BA08 R B Edelman
6633 Canoga Ave
Canoga Park CA 91303-2703

Rockwell Intrntl Sci Ctr
Attn S Chakravarthy
Attn S Palaniswamy
1049 Camino Dos Rios
Thousand Oaks CA 91360

SAIC
Attn M Palmer
1710 Goodridge Dr
McLean VA 22102

SRI Intrntl Propulsion Sci Div
Attn Techl Lib
333 Ravenwood Ave
Menlo Park CA 94025-3493

Sverdrup Techlgy Inc
Attn J Deur
2001 Aerospace Parkway
Brook Park OH 44142

Thiokol Corp Elkton Div
Attn R Biddle
Attn R Willer
Attn Techl Lib
PO Box 241
Elkton MD 21921-0241

Universal Propulsion Company
Attn H J McSpadden
25401 North Central Ave
Phoenix AZ 85027-7837

Veritay Techlgy Inc
Attn E Fisher
4845 Millersport Hwy
East Amherst NY 14501-0305

US Army Rsrch Lab
Attn AMSRL-WM-P A Horst
Attn AMSRL-WT-PA G Keller
Attn AMSRL-WT-PA T Minor
Attn AMSRL-WT-PA K White
Attn AMSRL-WT-PA L M Chang (5 copies)

US Army Rsrch Lab (cont'd)
Attn AMSRL-WT-PA P Conroy
Attn AMSRL-WT-PA D Kooker
Attn AMSRL-WT-PA T Rosenberger
Attn AMSRL-WT-PA A Brant
Attn AMSRL-WT-PA S Howard (5 copies)
Attn AMSRL-WT-PA D Kruczynski
Attn AMSRL-WT-PA C Ruth
Attn AMSRL-WT-PA I Stobie
Attn AMSRL-CI-LP (305)
Attn AMSRL-CS-AP D Kirk
Attn AMSRL-IS-C M Hirschberg
Attn AMSRL-IS-C R Kaste
Attn AMSRL-IS-CI A Celmins
Attn AMSRL-SC-HA W Sturek
Attn AMSRL-SE-RM R Tan (5 copies)
Attn AMSRL-SL-I D Haskell
Attn AMSRL-WM-TD A Dierich
Attn AMSRL-WM-TD K Frank
Attn AMSRL-WM-WB F Brandon
Attn AMSRL-WT-PA J Colburn
Attn AMSRL-WT-PB P Plostins
Attn AMSRL-WT-PC M Miller
Attn AMSRL-WT-T W F Morrison
Attn AMSRL-IS-CS A Mark
Attn AMSRL-WM-TB R Frey
Attn AMSRL-WM-TC B Sorenson
Attn AMSRL-WM-TC F Grace
Attn AMSRL-WT-TC De Rosset
Attn AMSRL-CI W H Mermagen Sr
Attn AMSRL-SL J Smith
Aberdeen Proving Ground MD 21005

US Army Rsrch Lab
Attn AMSRL-WM-WA A Baran
Attn AMSRL-WT-W H Rogers
Aberdeen Proving Ground MD 21010-5423

US Army Rsrch Lab
Attn AMSRL-CI-LL Techl Lib (3 copies)
Attn AMSRL-CS-AL-TA Mail & Records Mgmt
Attn AMSRL-CS-AL-TP Techl Pub (3 copies)
Attn AMSRL-SE-D E Scannell (5 copies)
Attn AMSRL-SE-DE S Kaplan (5 copies)
Adelphi MD 20783-1197

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
September 1997

3. REPORT TYPE AND DATES COVERED
Final, from May 1996 to January 1997

4. TITLE AND SUBTITLE
An Experimental Microwave Heating System for a 120-mm Munition

5. FUNDING NUMBERS
PE: 62120

6. AUTHOR(S)
Robert Tan, Tim Vong, and Stephen Howard

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
2800 Powder Mill Road
Attn: AMSRL-SE-RM
Adelphi, MD 20783-1197

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-TR-1317

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
2800 Powder Mill Road
Adelphi, MD 20783-1197

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
AMS code: 622120.1400011
ARL PR: 6WM841

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This report details an experimental microwave heating system designed for use with a 120-mm munition. The system operates at 2.45 GHz, using slotted waveguide radiators. The reported temperature measurements show relatively uniform heating of a surrogate 120-mm munition. Experiments at the Army Research Laboratory have shown that a munition's propellant heated for a few minutes by microwaves to 49°C has characteristics similar to those of propellant that has been temperature-conditioned to 49°C for several hours. In particular, this heating increases the munition's muzzle velocity about 5 percent, thus enhancing its performance.

14. SUBJECT TERMS
Microwave, heating, munition, slotted waveguide

15. NUMBER OF PAGES
26

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102